Energy for Sustainable Development 57 (2020) 12–21

Contents lists available at ScienceDirect

Energy for Sustainable Development

Understanding sustainable operation of micro-hydropower: a field study in Nepal☆

Joe Butchers [a,]*, Sam Williamson [a], Julian Booker [a], Anh Tran [b], Prem Bikram Karki [c], Biraj Gautam [c]

[a] Electrical Energy Management Group, University of Bristol, Bristol, UK
[b] Modern Energy Cooking Services Programme, School of Social Sciences and Humanities, Loughborough University, UK
[c] People, Energy and Environment Development Association, Kathmandu, Nepal

ARTICLE INFO

Article history:
Received 6 December 2019
Revised 13 April 2020
Accepted 13 April 2020
Available online xxxx

Keywords:
Micro-hydropower
Sustainability
Reliability
Assessment
Maintenance
Community

ABSTRACT

Off-grid renewable energy technologies are important in improving electricity access for rural communities. However, methods for ensuring their sustainable operation are often poorly understood. In this article, existing approaches for the assessment of off-grid projects are examined. Reliability of the technology, financial viability and community engagement are identified as the 3 key areas governing the sustainability of projects. Focusing on these areas, a methodology is proposed to understand the sustainability of micro-hydropower plants. A mixed-methods approach including a maintenance assessment and interviews with managers, operators and consumers is used to evaluate 24 sites in Nepal. Technically, the results of the study showed that trained operators delivered a higher standard of maintenance, however, technical issues were identified that arise during the design, manufacture and installation phases. The financial viability of plants was aided by charging consumers based on consumption, whilst plants with a higher rated capacity tended to benefit from a larger number of productive end uses. Community engagement was fostered through the local identity of the plant however this was threatened by societal changes. Inherent features of the site, such as rated power and the population density, internal resilience to short-term shock events (failure of components, insufficient collection of tariffs and departure of trained operators) and long-term external development (increased incomes, increased energy consumptions and growth in rural settlements) were found to affect the sustainability of plants.

Introduction

The United Nation's 7th Sustainable Development Goal 7 is to *ensure access to affordable, reliable, sustainable and modern energy for all* (United Nations, 2019). To achieve this goal, providing electricity access to the estimated 0.9 billion people in rural areas currently living without electricity is a key challenge (International Energy Agency, 2017). In these rural areas, off-grid technologies that are owned and operated by the local community can be effective in providing electricity and delivering developmental benefits (Bhattacharyya, 2013; Alstone, Gershenson, & Kammen, 2015; Gurung, Gurung, & Oh, 2011). However, the combination of technical, economic and social factors that can lead to the unsustainable operation of these systems is often poorly understood (Terrapon-Pfaff et al., 2014a; Hong & Abe, 2012; Ferrer-Martí et al., 2012; Schnitzer et al., 2014).

Micro-hydropower, generation at <100 kW, is an off-grid technology that has been used to provide electricity services to people located in off-grid areas of hilly and mountainous countries (Paish, 2002). In Nepal, the work of development agencies, industry, government and local communities has led to the construction of an estimated 3300 micro-hydropower plants (MHPs) (Nepal Micro Hydro Development Association, 2019a). Their construction can lead to improvements to livelihoods, health and education (Gurung et al., 2011; Legros, Rijal, & Seyedi, 2011), however, poor reliability of these hydropower plants has also been reported. Research has identified particular technical problems (Arter, 2011; Kumar et al., 2015; Khennas & Barnett, 2000) but post-installation monitoring of projects is often poor and rarely evaluates the actions of managers, operators and the community. To understand these technical problems alongside social and economic factors, it is beneficial to consider all of the technical and social elements (including organisational structures and social practices) as a socio-technical system (Ulsrud et al., 2015). This approach considers the local context, the relationships between technology and people, and the ways these relationships change with time (Ulsrud et al., 2015; Ulsrud et al., 2011; Ahlborg & Sjöstedt, 2015).

In this paper, a methodology is adopted to assess the key factors affecting the sustainability of micro-hydropower projects. In

☆ This study was funded by the Cabot Institute for the Environment, and a studentship from the Engineering and Physical Sciences Research Council, award reference 188052. Data are available at the University of Bristol data repository, data.bris, at https://doi.org/10.5523/bris.1k9cigxbcdiye22kuay4wbt5yu.

* Corresponding author.
E-mail address: joe.butchers@bristol.ac.uk (J. Butchers).

https://doi.org/10.1016/j.esd.2020.04.007
0973-0826/

Section Approaches to sustainability assessment, firstly, existing literature regarding sustainability assessments of mini-grid projects is evaluated; secondly, research specific to assessment of micro-hydropower plants is presented. Section Methodology introduces a combined qualitative and quantitative methodology. Section Results presents the key findings from 24 MHPs in Nepal relating to reliability, financial viability and community engagement. Section Discussion discusses the contribution of these factors to the sustainability of plants and makes recommendations. Section Conclusion presents the conclusions and suggestions for further work.

Approaches to sustainability assessment

In the available literature, approaches for assessing sustainability of renewable energy projects differ considerably. Varying interpretations in both the definition of sustainability and the purpose of a sustainability assessment leads to a range of approaches. By analysing a range of existing approaches to sustainability assessment, common factors within the literature could be identified. As these factors could be non-technical, it was considered important to analyse literature covering a range of renewable energy technologies. For ease of comparison, many assessments use numerical indicators to score different elements related to sustainability. Ilskog (2008) developed a method for evaluating sustainability of energy projects based on 39 indicators covering five dimensions of sustainability: technical, economic, social/ethical, environmental and institutional. The method is useful for comparing the sustainability of a range of rural electrification projects (Ilskog & Kjellström, 2008; Bhattacharyya, 2012). Mainali & Silveira (2015) used a similar approach based on evaluating numerous indicators across the same five dimensions as Ilskog. By considering energy projects on three occasions at 5-year intervals, their method provides an insight into how the sustainability of a project may vary with time. These quantitative approaches are useful in delivering a comparison between different technologies installed into different contexts. They can be used effectively as high-level planning tools, but their results do not provide detail on specific challenges nor lead to recommendations that can be easily implemented in the field.

Terrapon-Pfaff et al. (2014b) argue that there have been few studies that have specifically addressed the impact and post-installation sustainability of community-based projects. These authors use a combination of surveys and supporting empirical data to assess the sustainability of 23 projects located in 17 countries (Terrapon-Pfaff et al., 2014a). The results demonstrated that the technical sustainability of projects did not depend on the reliability of the implemented technology alone. It also depended on how the technology was embedded into the socio-cultural, political and ecological context. Across all 23 projects, knowledge, maintenance capability, user satisfaction and community ownership were identified as key factors in promoting sustainability. Schnitzer et al. (2014) considered best practices in the development of 17 mini-grid projects across several countries. They identified that to be sustainable, a threshold of reliability and financial viability should be maintained over a project's lifetime. They found that the connection of technical, economic and social factors in the operation of mini-grids would tend to drive projects into either “vicious” or “virtuous” cycles. An example of a “virtuous” cycle was when effective tariff collection led to high-quality operation and maintenance (O&M), resulting in a reliable energy service. Conversely, a “vicious” cycle could develop due to poor tariff collection leading to insufficient funds for maintenance resulting in a poor quality of service.

In a comparative study of 3 wind projects in Peru, Ferrer-Martí et al. (2012) were able to contrast the successes and failures that occurred with different technologies and management methods. Similar to the cycles identified by Schnitzer et al., it was observed that shortages of energy affected the satisfaction of beneficiaries and consequently their engagement with the project. Hong & Abe (2012) focussed on the social challenges and impacts of implementing an off-grid solar plant in the Philippines. They used interviews with a range of stakeholders and a survey of members of the project's co-operative. They found that despite providing reliable power at a reasonable cost, the obligation of a monthly payment was too much for some consumers. As a consequence, the tariff was reduced, broken parts could not be replaced, and the quality of service suffered. They identified capacity development and promoting productive end uses of electricity as key factors in improving the sustainability of the project.

Within the micro-hydropower sector, Arnaiz et al. (2018) developed a framework for assessing the success of projects in Nepal, Bolivia, Cambodia and the Philippines. The methodology used qualitative data from interviews with a range of stakeholders to provide numerical scores to several criteria. Whilst the numerical approach allowed for easy comparison between the countries, the information from interviews also provided valuable insights. The results of the study indicated that the Nepali schemes were most successful due to better construction, maintenance and ongoing governmental support. With a specific focus on Nepal, Bhandari, Saptalena, & Kusch (2018) developed a detailed sustainability assessment model. The study used interviews with households, management, an operator and micro-hydro experts to develop a list of 54 indicators specifically relating to the sustainability of micro-hydropower projects in the Nepali context. These indicators are carefully selected and allow specific dimensions of sustainability to be compared. However, the numerical results are unable to provide extensive details on specific threats to sustainability.

In Nepal, research in the micro-hydropower sector has specifically focused on the technical issues that can occur (Arter, 2011; Kumar et al., 2015; Khennas & Barnett, 2000). Several studies have indicated that the quality of turbines can be low; poorly fabricated and installed pulleys have led to premature wear in belts and bearings (Arter, 2011; Kumar et al., 2015). The construction of civil structures is often mentioned as a cause of problems due to overly long and poorly designed canals (Khennas & Barnett, 2000; Gill, Moseley, & Fulford, 1999). A lack of supervision from installation companies during the civil works, particularly for the de-silting bay, can result in increased turbine erosion (Kumar et al., 2015). These studies have demonstrated technical issues that occur at MHPs, but rarely have they considered the interaction of the operational team, the community and the technology once a project goes into operation. An exception is Barr's (Barr, 2013) study of 6 sites which documented technical problems that occurred once a plant goes into operation, and showed that operators' approaches to maintenance were affected by the economic opportunities in the local area.

The previous research on sustainability assessment has established that it depends on multiple drivers. Assessments using qualitative rather than quantitative approaches were able to provide greater insight into specific challenges. The literature suggests that to achieve sustainability, a project must operate reliably, providing the community with household and commercial benefits that ensure their financial and social engagement. Within the micro-hydropower field, technical issues and a connection between maintenance quality & economic activity have been identified. However, studies have not documented the actions and perspectives of operators, managers and communities. Consequently, this paper proposes a methodology to understand the sustainability of micro-hydropower plants. In this context, the sustainability of a micro-hydropower plant is defined as the ability of the technology and its stakeholders to deliver electricity services that meet the expectations of consumers over a system's expected lifespan. To understand this, the methodology described in Section Methodology evaluates; the specific threats to reliability; the capability and typical behaviour of the operators and management team; the types of load and the income they generate; and the factors that lead to successful engagement of the community. Combining this information can be used to understand the three key areas (identified in this section) that influence the sustainable operation of plants: technical reliability, financial viability and community engagement.

Methodology

The methodology used includes a combination of quantitative and qualitative methods that are focused on understanding the reliability, financial viability and level of community engagement. These three areas were compared between the different sites, providing an opportunity to evaluate their contribution to the sustainability of plants. As each site visit was completed on a single day, the results of the study are not effective in making a specific assessment of the sustainability of individual plants. Greater historical knowledge, more detailed financial information and an understanding of external threats in each location would be required to give an accurate prediction of an individual plant's sustainability. However, the experiences from all the sites can be used to understand and compare the contribution of these factors.

For power supply systems of all sizes, reliability can be considered in two parts: the amount of energy delivered over a certain period of time and the system's ability to respond to disturbances (Numminen & Lund, 2019; Billinton, Allan, & Power, 1984; Rausand & Høyland, 2003). Usually, numerical data is used to quantify these two parts, for example, using the amount of power delivered and the operational time lost due to failures (Numminen & Lund, 2019). In our case, it was not possible to access such data due to a lack of recorded information. Within this study, reliability is defined as the ability of the system to consistently deliver the expected electricity service whilst avoiding failures. To operate reliably, each of the sub-systems of the MHP should be maintained to avoid failure and function as designed, allowing the required power output to be delivered. To assess reliability, a two-part evaluation was conducted at the following 10 sub-systems: intake, de-silting bay, canal, forebay tank, penstock, powerhouse, internal pipework, turbine, control panel, and generator. Fig. 1 identifies these sub-systems and their location within a typical MHP.

At each sub-system, the evaluation consisted of a qualitative inspection and a quantitative assessment of the quality of maintenance. The purpose of the qualitative inspection was to visually identify threats that could reduce power output or lead to failure. The observations from inspection were recorded on site and documented using photography. The purpose of the quantitative assessment was to rate the quality of maintenance at each sub-system. A marking scheme was used that had been developed based on available literature (Legros et al., 2011; Khennas & Barnett, 2000; Ulsrud et al., 2015). Table 1 shows an example of the marking scheme used to assess the de-silting bay. In the marking process, scores were assigned as discrete values (e.g. 1, 2, 3, 4 or 5).

Table 1
Marking scheme for the de-silting bay.

Description	Score
Very well maintained. Good evidence of regular preventative maintenance. De-silting bay is clean, free from erosion with no obvious cracks visible. Minimal silt build up.	5
Evidence of effort to maintain the sub-system but without following a schedule closely. Some dirt, debris and a small amount of erosion is visible. Cracks may be present, but they are small. Any obvious leaking is minor. Some silt is obvious in bottom of bay.	3
Poorly maintained. Preventative maintenance is rare. Intake is heavily contaminated with obvious signs of erosion. Cracks are significant and/or leakage is obvious. Significant build-up of silt in bottom of bay.	1

The assessment and observations were supported by a semi-structured interview with the plant operator which documented their responsibilities, actions and opinions. In this study, in the time available and with many of the turbines in operation, this two-part assessment was deemed an appropriate method to provide an indication of reliability. The nature of the assessment meant that it was only possible to assess the maintenance and identify threats at the time of inspection. Whilst this approach could not provide a value for the overall reliability, it allowed comparison between the sub-systems, technologies and plants.

To gain alternative perspectives on the plant's reliability and an understanding of the financial viability and community engagement, semi-structured interviews were conducted with a plant manager and a consumer at each site. With the manager, the interview also explored the current economic status of the hydropower plant, its organisational

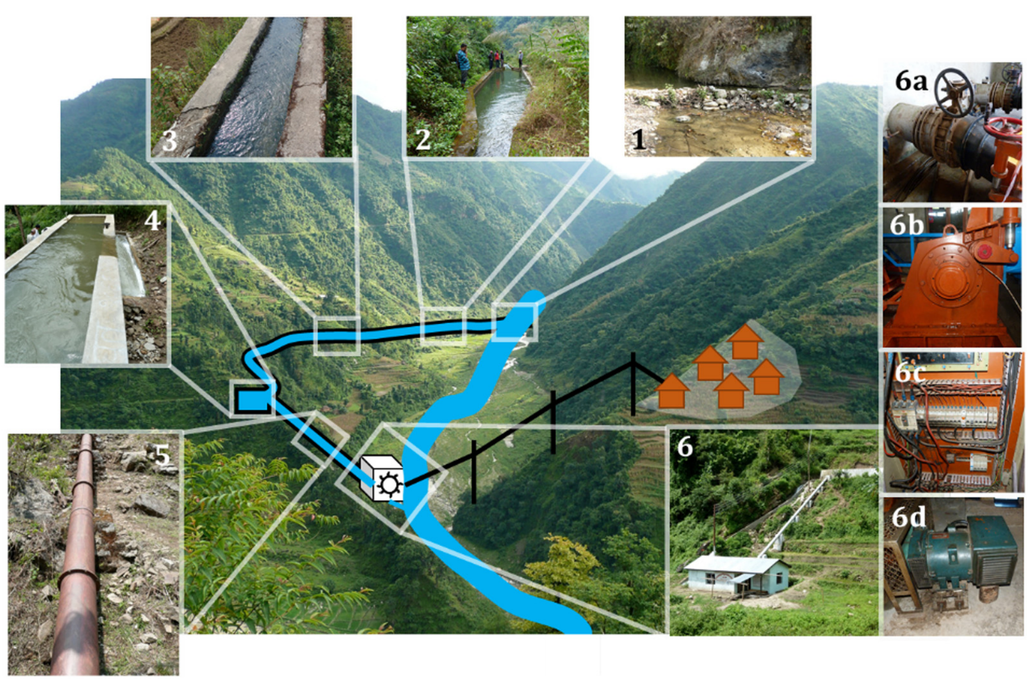

Fig. 1. Constituent sub-systems of a micro-hydropower plant. Labels indicate the following: 1. Intake, 2. De-silting bay, 3. Canal, 4. Forebay tank, 5. Penstock, 6. Powerhouse, 6a. Internal pipework, 6b. Turbine, 6c. Control panel, 6d. Generator. Adapted from Sumanik-Leary et al. (2014).

structure and the actions performed by the management team. Interviews with consumers were used to understand their opinion of the hydropower plant, their personal electricity use and expenditure. Previous experience of the authors and the literature review helped to focus questions to the specific Nepali context. A total of 50 interviews were conducted in Nepali and subsequently translated into English. Where possible, interviews were conducted in isolation though due to cultural conventions, this was not always possible. Interviewees were made aware that it was an independent study for research, and it would have no financial impact on the individual nor the plant. Due to the focussed sample size, the responses gathered from consumers were used to understand their perspectives rather than draw specific conclusions about the individual projects.

Due to its terrain and infrastructure, travelling to remote areas of Nepal is expensive and time consuming. As there are MHPs located in at least 45 of Nepal's 75 districts (Basnet, 2014), a study representative of the country would have visited sites in a larger number of districts. Unfortunately, the budget for the study dictated a choice between visiting a small number of sites (< 5) in several different districts or a larger number (> 20) in a single or neighbouring districts. It was decided that visiting a larger number of sites would be advantageous for several reasons. There was likely to be less variation in the socio-economic landscape than across multiple districts and it was possible to develop a greater understanding of the local context. Proximity to turbine manufacturers, mostly in Butwal and Kathmandu, and suppliers of parts was deemed an important factor in a plant's reliability. Within a smaller geographical area, the difference between sites was in the order of hours rather than days.

To visit at least 20 sites within a small geographical area, the neighbouring districts of Baglung and Gulmi, located in Gandaki Pradesh and Province No. 5 respectively, were identified as a region with a high density of MHPs. These districts have reasonable road access and a high density of MHPs. A list of 30 potential plants was considered, where the contact details were known, and the sites could be reached within a single day from the main road, the Mid Hill Highway. From these 30 sites, a total of 24 sites were visited. Table 2 outlines the ranges in the site characteristics. There was variation in the size and types of turbine; distance from a main road; and the number of households connected to the MHP.

The majority of the sites (22 of the 24) were located in Baglung district where historically many MHPs have been constructed. In 2009, Baglung was the only district in Nepal where >1 MW of mini- & micro-hydropower had been installed (Alternative Energy Promotion Center, 2009). The topology of the visited districts is more favourable to Crossflow than Pelton turbines which accounted for the larger proportion of turbines of this type. Generally, Crossflow turbines are used at sites with lower heads and higher flow rates, whilst Pelton turbines are used for sites with higher heads and lower flow rates (Paish, 2002). Their distinct designs can result in different issues relating to reliability and performance. The location of the sites visited is a limitation of the study and should be considered when analysing the results. In relation to reliability, all of the sites in the study could be reached in less than a day from Butwal, where many turbine manufacturers are based. This means spare parts can be delivered and maintenance carried out a lot more quickly than in remote districts in the far East and West of Nepal. These factors suggest that the technical reliability of the sites is likely to be better than sites located in more remote areas; the findings should be considered in this context. From a socio-economic perspective, both districts are below the national average in terms of per capita income and human development index (Sharma, Guha-Khasnobis, & Khanal, 2014).

Table 2
- Characteristics of the 24 visited sites.

Characteristic	Range
Number of connected households	94 to 1765
Rated power (kW)	18 to 135
Types of turbine	18 Crossflow, 6 Pelton
Time to powerhouse from main road (hours)[a]	0 to 6
Year since commissioning	1 to 18

[a] Journeys were made by vehicle, on foot or a combination.

Results

Reliability

From the numerical assessment of maintenance, a notable outcome was the difference in the quality of maintenance delivered by trained and untrained operators. Most operators receive 22 days of technical training from the Nepal Micro-Hydro Development Association or an accredited training company (Nepal Micro Hydro Development Association, 2019b). The training includes sessions that teach operators preventative maintenance tasks and the function of all of the sub-systems assessed during the study (Nepal Micro Hydro Development Association, 2014). Following the training, the expectation is that operators will be able to operate the plant, carry out preventative maintenance tasks, identify basic faults and replace a number of components, e.g. bearings, fuses and transmission belts (Barr, 2013). When a significant problem occurs, representatives of the manufacturing company will visit the MHP to carry out repairs. At all the sites visited, operators were paid for their work with their monthly salaries ranging between NPR 4500 ($44, at the time of the study) and NPR 15,000 ($147). However, at 9 sites operators had left their job, typically moving abroad for employment. The operators who replaced them had not received any formal training. Fig. 2 shows the mean scores of sub-system assessments by site for trained and untrained operators. The vertical dashed line is the mean ($\bar{x} = 3.16$) of all the sites suggesting (as per the marking scheme) that on average there was evidence of maintenance effort but without following a schedule closely. There were 9 sites with mean scores below 3, and 7 of these had untrained operators.

An independent samples *t*-test was used to look for significant differences between the mean scores of trained and untrained operators. Table 3 shows the results that have been accepted as significantly different at the 1% and 5% confidence interval levels. It found that there were statistically significant differences in the overall mean and for the control panel, internal pipework and turbine sub-systems. In the table, *M* and *SD* represent the sample mean and standard deviation respectively. Meanwhile, *t* (*t*-value) represents the size of the difference relative to the sample data which is used to give a corresponding *p* (*p*-value) which is the significance of the result. The significance of the results suggests that overall and for the 3 particular sub-systems, there is a very high probability that the same trend of worse maintenance by untrained operators would apply for the whole population. However, several factors are important in analysing these results. Firstly, the assessment was a one-off. Maintenance scores were given based on an instant assessment without knowledge of an operator's typical routine. Secondly, the assessment was made without stopping the turbine. It was not possible to evaluate some performance critical components, particularly the turbine runner. Thirdly, some of the sites visited were easier to maintain than others. For example, it is much less time consuming to maintaining a short canal than a long canal. Finally, even amongst operators who had attended training, each training course was different and their attainment within the course unknown. These factors should be considered when analysing the statistical results. On a simplistic level, there is evidence that trained operators delivered a higher standard maintenance. However, the factors noted above should be considered when discussing the results in relation to the whole population.

For the 3 sub-systems listed in Table 3, there were common problems observed which reduced the maintenance score attained by untrained operators. The electrical components were often poorly

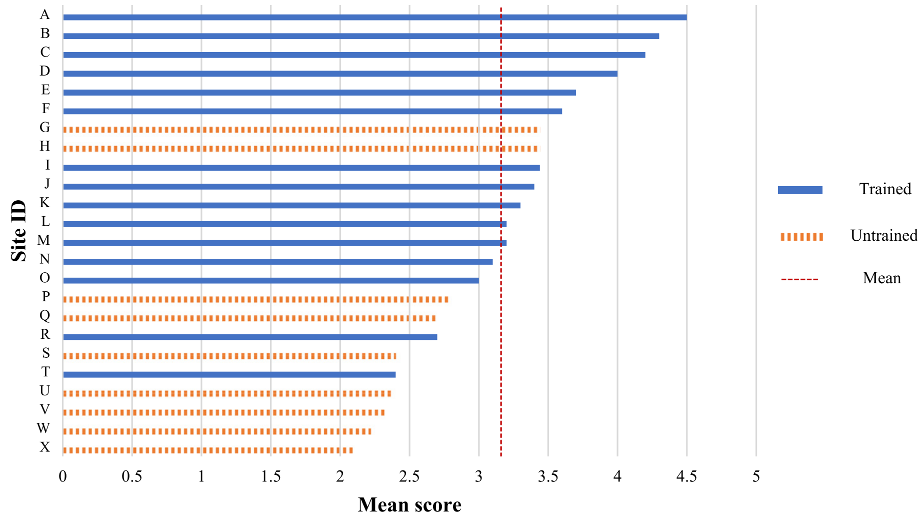

Fig. 2. Average maintenance scores by site. Adapted from Butchers et al. (2018).

maintained; inside control panels, there were loose cable clamps and wires pulled from their conduit. For both turbines and the internal pipework, leakage as shown in Fig. 3, rust and loose bolts were common. For hydropower systems, leakage can reduce the overall turbine efficiency due to a loss in pressure and flow rate.

Amongst all the operators, the maintenance of civil structures was a weakness. The walls of canals were often cracked due to plant growth which resulted in leakage. The growth of moss reduced accessibility as typically walls of the canal are used to reach other civil structures. Alongside the maintenance issues, there were issues with the original construction of some civil structures. A commonly observed problem was poorly shaped forebay tanks and de-silting bays. Typically, these sub-systems are located before entering the main canal section and later before reaching the penstock. Their critical function is to reduce the quantity of silt flowing through the system; small particles of material suspended in the flow of water can be abrasive to the turbine runner (Harvey, 1993). The shape of the tank slows the speed of the flow using a symmetrical divergent section, the particles settle on the floor of the tank allowing them to be flushed away. When these tanks are incorrectly shaped, they failed to decelerate the flow and are ineffective in settling silt. An example is shown in Fig. 4, the divergent section of the tank is asymmetrical allowing the flow to continue quickly along one wall.

Mechanical issues were also identified that can manifest at a number of stages. Large vibrations in transmission belts was commonly observed. As a mechanical system, vibrations in the system will cause movement which alters alignment and changes the belt tension. During operation, the plant operator is responsible for correcting this issue, but it is possible that poor design and low quality in manufacture contributed to the problem initially. All of the issues listed in Table 4 have an impact on the turbine when in operation and should be addressed by the operator accordingly. However, for many of these problems, greater attention to detail in an earlier stage of the project can minimise their effect.

Plant operators were asked about the frequency with which they performed various tasks. For activities in the powerhouse, the practice of operators was mostly in line with expectation. Of the 24 operators, 19 said that they checked the noise and temperature of bearings daily. Usually bearings should be greased every 500 h although smaller bearings will likely require less frequent greasing (Thake, 2000). This suggests that greasing approximately every 2–4 weeks is a reasonable frequency. Of the operators, 14 gave a response that was within that time period, 8 said they did it more frequently and 2 less. At several sites, there was evidence of over-greasing, suggesting either greasing too frequently or applying too much grease each time. Over-greasing causes bearings to overheat as grease is churned away from rotating elements (Harvey, 1993), it can also harden due to the heat and later prevent the ingress of new grease (Lugt, 2009).

Outside of the powerhouse, there was a lot more variation in what operators considered to be the correct frequency for various maintenance activities. Draining the de-silting bay and forebay tank are important activities to ensure that the build-up of collected silt does not pass through the turbine. In the monsoon season, heavy rains bring large amounts of silt and debris into micro-hydro systems. In this period, it is important to flush out the civil structures more frequently; half of

Table 3
t-test results for trained and untrained operators. Adapted from Butchers et al. (2018).

Type	Trained		Untrained		t	p	Significance level
	M	SD	M	SD			
Overall	3.47	0.59	2.62	0.49	3.49	0.002	1%
Control panel and other electrical	3.93	0.80	2.72	1.03	3.22	0.004	1%
Internal pipework	3.80	1.15	2.44	0.88	3.04	0.006	1%
Turbine	3.47	0.99	2.44	1.13	2.32	0.030	5%

Fig. 3. Leakage from a turbine casing.

Fig. 4. Ineffective shape of de-silting bay.

the operators acknowledged the need to do this. A simple task that should be performed at least every other day is cleaning the trash rack (Harvey, 1993). Amongst the operators, 11 of the 24 did it with this frequency. This variation between operators demonstrates a threat to plant sustainability.

To maximise reliability of the system, there is a minimum frequency with which maintenance activities should be carried out. It is the responsibility of the plant operator to carry out these tasks; however, only 1 of the 24 sites had a maintenance schedule that the operator followed. Without a schedule, there is no means for the plant managers to check whether maintenance has been completed at the right time. Typically, this resulted in a maintenance approach was more often corrective than preventative.

Operators were asked to list all the components that had broken in the previous year and the parts that were kept as spares in the powerhouse. Fig. 5 shows the frequency of reported component failures and the frequency that the same parts were kept as spares. Across all the sites, the spare parts kept demonstrated there was an awareness of the parts most needed as spares. Turbine bearings were kept as spares at over 70% of sites ensuring many sites were ready to deal with the high proportion of bearing failures that were mentioned. Similarly, 25% of sites kept belts as spare parts whilst 29% mentioned a belt failure in the preceding year. In the figure, it can be seen that the electronic load controller (ELC) board was the second most failed component. During the study, it was observed that the ELCs at all of the sites were based on electronic “breadboards”; these designs have been used since the 1980s (Paish, 2002). Using modern power electronics manufacturing and devices, e.g. printed circuit boards, could improve the reliability of electrical components.

The results of the study suggested that trained operators could deliver a higher quality of maintenance than untrained operators. Their superior expertise was most obvious inside the powerhouse where there was evidence of preventative maintenance. Across all the sites, operators and managers responded to the common failures in bearings and belts by keeping spare parts ready for replacement. The qualitative inspection of sub-systems found threats to reliability that originated at the design, manufacture or installation stages.

Financial viability

During interviews, 3 forms of management structure were encountered; there were 2 private, 2 co-operatives and 20 community owned sites. Privately owned MHPs were run as a business with the proprietor(s) taking responsibility for management including tariff setting and financial management. In both co-operatives and community owned sites, periodic meetings allow beneficiaries to have input into decisions made regarding the MHPs and beneficiaries are often expected to provide labour when repairs are required. In the co-operative structure, consumers' initial labour and financial contribution give them a share in the MHP. For community owned plants, the relationship is not formalized. In all cases, plant managers are responsible for collecting tariffs from consumers. The management structure was not found to have a significant impact on the financial viability of the sites.

In total, 23 of the 24 sites charged consumers based on electricity meters fitted in their homes. The one exception was a site where electricity meters were not working, and a flat rate of NPR 200 ($2) was charged. At the other sites, tariffs were charged using a basic rate which permitted the use of a defined number of kilowatt-hours (kWh) with additional consumption beyond this limit charged on a per unit kWh basis. The basic rates varied considerably from between 4 and 20 kWh for NPR 100 ($1). Some sites used multiple tariffs structures to charge more for a higher current connection, meaning households with basic electricity needs (e.g. lighting and charging only) had a cheaper basic rate than those using higher current appliances. Using the tariffs charged by the Nepal Electricity Authority (2018), the national distributor, the cost of electricity from the MHPs can be compared with the national grid. Taking the basic rates for the MHPs and assuming a connection to the national grid at the lowest current rating of 5A, the equivalent cost for grid-based electricity can be calculated. In all but one case, the cost of electricity from the MHP was more expensive than from the grid. On average across all the sites, the cost of electricity from the grid is 33% cheaper.

At the sites visited, several methods were used to collect the tariffs. Some sites located in more densely populated villages instructed consumers to make the payment at the plant's office within a certain period in each month. At others, management employees would collect money from consumers' homes. At some sites with more dispersed houses, the tariffs were collected by beneficiary groups who were responsible for bringing it to the managing committee. One management representative highlighted this as a problem describing their beneficiary zone as

Table 4
Issues identified at each sub-system and the project phases affected. Adapted from Butchers et al. (2018).

Subsystem	Major issue (s)	Design	Manufacture	Construction	Installation	Maintenance
Intake and weir	Temporary structures require repair or reconstruction after each monsoon	●		●		●
De-silting bay	Poor shape limits settling of silt	●		●		●
Canal	Landslides make regular repair necessary			●		●
Forebay tank	Poor shape limits settling of silt	●		●		●
Penstock	Ineffective drainage away from penstock foundations			●		●
Powerhouse	Dirty and cluttered spaces					●
Internal pipework and valves	Water leakage	●	●		●	●
Turbine	Water leakage	●	●		●	●
	Shaft and transmission belt misalignment	●	●		●	●
Control panel, cabling and ballast	Dangerous cable routing				●	●
Generator	Transmission belt misalignment	●	●		●	●

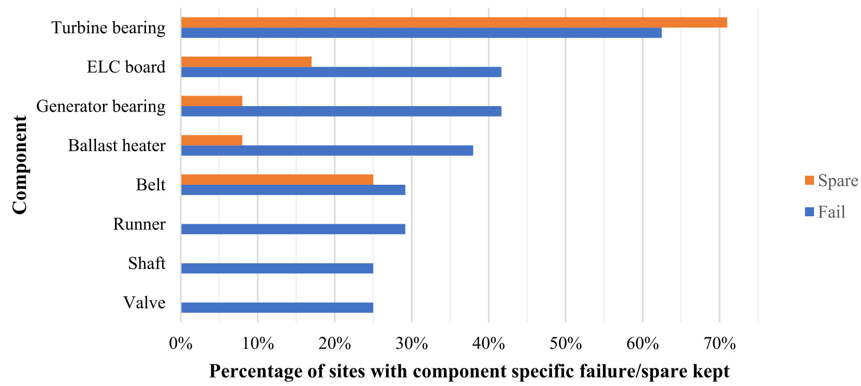

Fig. 5. Percentage of sites with component specific failures / spare parts kept.

"scattered". Another manager explained that amongst the 26 beneficiary groups, there were some that had not paid their bills for 15 months and with some of these groups >6 h walk away, collecting tariffs was very time consuming.

Alongside household connections, MHPs are also used to power commercial connections or productive end uses. The term productive end use is used to describe a use of electricity that increase income or productivity (Brüderle, Attigah, & Bodenbender, 2011). Historically, hydropower has been used to drive machinery for agro-processing, however, electricity generation allows greater diversity in the types of productive end use. In this study, the end uses of electricity across all of the sites were highly varied. Table 5 groups these end uses into 3 categories: industrial services, commercial services and community services. Industrial services included traditional agro-processing such as flour and grain milling, but also a range of less conventional industries including a factory for processing cotton and another for making noodles. Commercial services were dominated by shops, however, other uses included mobile phone masts and radio towers. Many community services were powered by hydropower plants including 84 schools, 40 hospital/health clinics and 9 community centres. The different types of end uses will use electricity during different times in the day. Whilst households use most of their electricity in the early morning and evenings, industrial services will often use electricity during daylight hours. Other connections such as telecom towers and hospitals may use electricity for 24 h in a day. These end uses that consume electricity continuously demonstrate the broader impact that MHPs have in rural areas. Significant tangential benefits are delivered through these services to the wider community, and not only to paying customers of a hydropower plant.

Diversity in the types of end use is an important feature in achieving financial viability. Having a range of end uses can maximise the hours in the day when electricity is used and the plant is generating an income. To understand this diversity, Fig. 6 plots the number of different types of productive end use at each site against the number of connected households. The number of different types of end use gives an impression of the diversity of commercial, industrial and community services at that site. As the number of connected households increases, the trend is that the diversity in end uses also increases. In general, the larger settlements in the study had greater variety in the types of end use making those MHPs more likely to generate income throughout the day.

Income is generated from both household and commercial connections. Fig. 7 shows the number of connected households and connected end uses against rated power. The area of a marker represents the number of end uses that are connected to that MHP. The markers are coloured according to the manager's response to the following question: *"When there have been technical problems, has there been enough money to pay for repairs?"* Responses to this question have been coded as "mostly yes", "sometimes yes/no" and "mostly no" and give an indication of the financial viability of the plant. The site with the highest rated power has been removed as its connection to a stone thresher with a typical load of 100 kW skewed the results in relation to the number of connected end uses ($n = 81$).

The obvious trend is that the number of households is positively correlated to the rated power of the site. There is also a weaker positive

Table 5
Types of productive end use at the 24 sites.

Commercial services	Total	Industrial services	Total	Community services	Total
Grocery shop	353	Flour/grain mill	85	School	84
Tea shop	164	Poultry Farm	58	Hospital/health clinic	40
Bank/Co-operative	28	Furniture making	37	Local government office	35
Clothing shop	31	Welding workshop	19	Post office	7
Hotel/Lodge	16	Bakery	10	Community centre	9
Barber shop	9	Dairy shop/factory	4	Temple	2
Meat shop	8	Cotton factory	1		
Telecom tower	9	Stone thresher	1		
Radio tower	5	Noodle factory	1		
Computer training centre	3				
Stationary shop	3				
Irrigation pump	3				
Movie hall	1				
Petrol pump	1				
TV cable office	1				
Workshop/Garage	1				

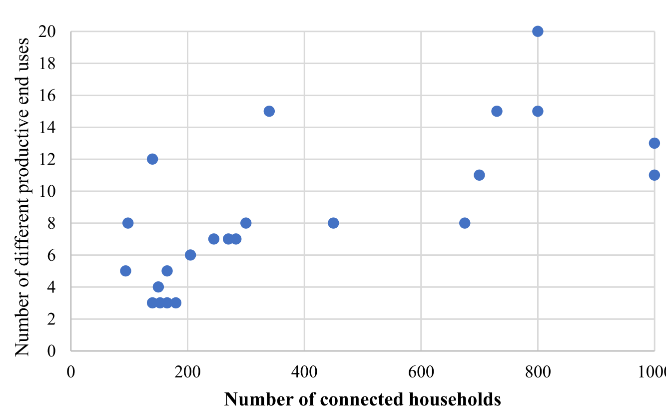

Fig. 6. Number of different productive end uses against the number of connected households.

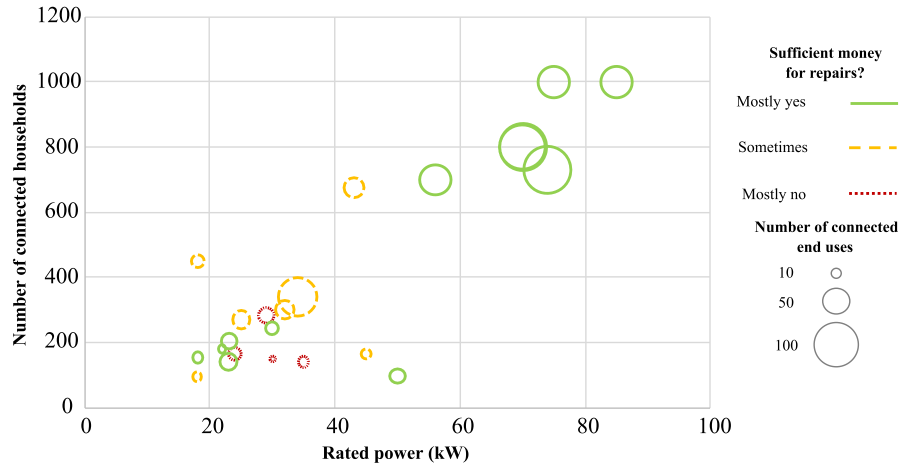

Fig. 7. Number of connected households and number of end uses against rated power. Adapted from Butchers et al. (2018).

correlation between the rated power and the number of connected end uses; mostly, the size of markers increases for higher rated power although there are some exceptions. Both relationships are assumed to be linearly correlated to site rated power with correlation coefficient r values of 0.86 (strong) and 0.68 (moderate) for households and end uses respectively. For the sites where there had been problems paying for repairs, 3 managers explained that additional funding was collected from beneficiaries. One respondent explained that "people are categorised into 3 groups depending upon [their] economic condition". This approach, also documented in Kumar et al. (2015), is unreliable and can lead to prolonged downtime whilst funds are collected. The results suggest that plants with higher rated power can connect both a larger number of connected households and end uses. Within the study, responses from managers indicated that their income of sites with rated power above 50 kW was usually sufficient to pay for repairs. With a higher number of connections, these plants are likely to benefit from a superior load factor, improving their financial viability (Kumar et al., 2015; Khennas & Barnett, 2000).

At the sites in the study, the use of electricity meters was almost universal allowing the plants to generate income accurately based on the amount of power consumed by users. There was variation in tariff structures and in the methods used for collecting income; sites in more densely populated settlements usually benefited from easier tariff collection. These also tended be sites with higher rated power (above 50 kW) that were able to connect more households and a large number of diverse end uses. Consequently, these sites were the most financially viable.

Community engagement

An aspect of community engagement is consumers' satisfaction with the service provided by the MHP. Table 6 shows the percentage of responses given to 3 questions that focused on the quality of service provided. For both the quality of service and its cost, consumers were largely positive. No consumer interviewed was unhappy with either the price they paid for electricity or considered the service to be unreliable. When asked about the impact that connection to the MHP had upon their lives, responses from consumers were wholly positive and included social, economic and health benefits. It was often mentioned that children could study at night and village social events were improved. Many mentioned their reduced expenditure; one respondent explained that their spending on lighting had reduced from NPR 500 ($5) to NPR 100 ($1) per month. Several chose to mention the benefit of reduced smoke in the home in comparison to using kerosene or candles. The consumer satisfaction largely translated into regular payment by consumers. At 92% of sites, manager representatives answered "Yes" or "Yes, mostly" when asked if consumers paid regularly. When consumers were asked about the effect of late payment, several referenced the potential social, economic and technical consequences. One respondent explained that "society shouts if [the bill is] not paid" whilst another said that "salaries will not be paid; maintenance repairs will not be on time".

At community owned MHPs, beyond simply making payments, committee members expect that consumers take part in meetings and assist with the maintenance of the civil works. Responses from managers suggested there was more variation in the level of community engagement between the sites. Some felt that there was a lack of interest from the community as "the beneficiaries do not try to understand" when problems occur. Another manager said that despite beneficiaries considering the MHP essential in their lives, there was "low interest and ownership from the community". It was noted by some that the economic condition of beneficiaries affected their ability to pay but they remained interested. Several other managers identified that there had been a change with time; decreasing power of the MHP, increase in the total load and the encroachment of the national grid were all mentioned as factors that lead to a reduction in community interest.

The prospect of the national grid is regularly discussed in rural areas; it is often used by local politicians to solicit votes in elections. Consumers were asked whether they would prefer to receive electricity from the national grid, though Table 6 shows that there was a mixed response from consumers. For those who stated that they would prefer electricity from the grid, several referred to the "temporary" nature of the civil structures of the MHP. Damage from landslides and the monsoon often lead to consumers needing to help in repairs and maintenance. Several consumers said that they would connect to the grid but felt that the decision should depend on the whole community. This was also true of 2 interviewees who were uncertain about connecting

Table 6
A selection of consumer responses.

"Are you happy with the price that you pay for electricity?"	
Yes	87.5% (21 of 24)
OK	12.5% (3 of 24)
No	0
"Is the supply reliable?"	
Yes	79.2% (19 of 24)
OK	20.8% (5 of 24)
No	0
"Would you prefer to be connected to the national grid?"	
Yes	29.2% (7 of 24)
Undecided	25% (6 of 24)
No	45.8% (11 of 24)

to the grid. For them, the decision needed to be made with the entire community; one respondent said that they did not want to be "left alone and behind". Amongst the 46% who had no interest in connecting to the grid, 3 more consumers chose to describe the MHP as "local". Another interviewee went further by emphasising the collective effort that had been exerted; they did not want to be connected to the national grid as "much hard work had been done for the local level MHP plant".

In most cases, the benefits and quality of service ensured that consumers paid regularly. The consumers were largely happy with the amount that they paid for electricity, with several mentioning that the cost of alternative sources was greater. Managers recognised that consumers paid regularly but that it did not always translate into a sense of ownership. Many managers felt that the level of ownership had changed with time. However, many consumers still identified strongly with the "localness" of the plant.

Discussion

The sustainability of plants in the study was affected by factors present before a plant begins operating. Plants that were located in larger villages, which were also located close to the main road, tended to have fewer problems in paying for repairs, due to a higher number and greater diversity of end uses. The proximity to the main road also enabled easier access for the repair or replacement of failed components. Financial management in larger settlements was aided by easier tariff collection, consumers came to pay at local offices rather than managers needing to walk long distances to collect payments. Technically, the actions of the operator should maintain the reliability at a certain level. However, there were problems identified that occurred due to poor design, manufacture or installation. An example was poorly shaped de-silting bays and forebay tanks as identified in (Kumar et al., 2015). The eventual outcome is that a greater amount of silt passes through the turbine which increases the wear rate of the runner, leading to the need to repair or replace parts sooner. Similarly, other identified issues like leakage and frequent failure of bearings could result from the actions of manufacturers rather than operators. There are also opportunities for manufacturers to integrate newer technology to improve reliability and fault detection. Utilising up to date power electronics manufacturing methods and devices, and integrating fault detection systems could be valuable improvements. Their availability, integration with existing sub-systems, and usage by plant operators would require detailed consideration. For operational mini-grids, Schnitzer et al. identified that once a mini-grid project enters operation, it can head into either a "virtuous" or "vicious" cycle (Schnitzer et al., 2014). The results of this study suggest that the original socio-economic, environmental and technical features of an MHP can increase the probability of heading in either of these directions.

Whilst a micro-hydropower site will have certain inherent features, the socio-technical system comprised of community, management and technology is dynamic (Ulsrud et al., 2015). Furthermore, the system resides in a broader socio-economic environment (Drinkwaard, Kirkels, & Romijn, 2010). In this study, there were numerous examples of changes, both internal and external, that affected the resilience of the socio-technical system. Internal events that were witnessed or described by interviewees included the failure of components, insufficient collection of tariffs or the departure of a trained operator. It is common for young Nepali men and women to seek work in urban areas or abroad and for MHPs, this can often lead to the departure of the highly skilled trained operators. These internal shock events result in an instantaneous or quick effect on the system, leading to a decrease in the financial viability or reliability of the plant. Changes that were external were more variable in their timespan. Development in rural Nepal, perhaps even due to an MHP itself, has resulted in changes in the socio-economic landscape where they reside. Rural settlements have grown; income and electricity consumption have increased. For MHPs, the consequences of these long-term changes can be both negative and positive. For some plants, this may reinforce the inherent benefits of being located in a larger settlement. An increasingly diverse range of end use connections and the higher electricity consumption of households will increase their financially viability. However, as the consumers at these sites may depend on running a business rather than agriculture; they may not be willing to give time to assist with the MHP. Furthermore, as rural settlements grow, it becomes more difficult to mobilise these communities en masse. External and internal events affect reliability, financial viability and consumer engagement both positively and negatively, and understanding these factors will improve the resilience and sustainability of MHP projects.

For sites with challenging inherent features like a low rated power or dispersed households, the sustainability is more fragile. When internal or external changes occur, it is important that effective maintenance, management and community engagement are all present to avoid entering a "vicious" cycle. The results of this study suggest that the training delivered by the NMHDA and supporting companies is effective in delivering a higher standard of maintenance. However, a greater focus on the maintenance of civil works and the turbine sub-system can improve the reliability and performance of plants. Operators replacing trained operators must receive training. Typically training takes place in Kathmandu or Butwal but local training for groups of untrained operators could be a more cost-effective approach. Alongside, the need for operators to know how to perform various maintenance tasks, it is important that they are performed with the correct frequency. Preventative maintenance of sub-systems is vital in ensuring their long-term reliability. Plant managers should be encouraged to implement a maintenance schedule allowing them to check whether operators are performing the necessary tasks at the correct time, and schedule more complex maintenance activities (at correct intervals) with a manufacturer. Currently, when there is insufficient money to pay for repairs, many plants collect funds on an ad-hoc basis. This approach is considered more culturally acceptable, with those able to pay expected to do so, but it is not financially viable in the long term. Given that consumers value their services and stated that they were willing to pay more, energy usage data could be used to find payment structures that balance the needs of the plant and the people. This study gathered information regarding tariffs, collecting data on the consumption of households and end uses would allow tariff structure models to be compared. Across the plants visited, both the level and need for community engagement varied. At smaller plants, consumers are usually expected to provide labour for repairs. However, at larger plants with greater income, reliability may be improved by paying for repairs works rather than relying on consumers. An improved understanding of consumer perspectives including how experiences vary depending on gender and caste would be beneficial in improving understanding of community engagement with MHPs.

The results of the study should also be considered within a wider context. In comparison to more remote districts that rely on micro-hydropower, the sites visited were largely accessible by road. The proliferation of MHPs within the study area means that there is a familiarity with hydropower; typically, communities have a good awareness of the project development process. Road access contributes to greater technical reliability but also greater access to markets, supporting the diversity of end uses found in the study. For sites in more remote, less accessible and less developed regions; the technical reliability and financial viability of MHPs is likely to be weaker. In addition, in more mountainous districts where distances between communities are greater, local knowledge regarding hydropower may be less concentrated. Even within the context of Baglung and Gulmi districts, threats to reliability, poor financial management and a lack of community engagement were witnessed. Therefore, despite the focussed geographical coverage of the study, one can expect that in more remote districts without a high density of MHPs, similar issues will occur. Furthermore, in these places with more challenging inherent features, the sustainability of plants is likely to be even more vulnerable. Using the same methodology at MHPs located in more remote districts would be valuable in understanding differences in the sustainability of plants, particularly in relation to technical reliability.

Within Nepal recently, governmental and non-governmental organisations have placed a greater focus on improving the sustainability of micro-hydropower plants. Renewable Energy for Rural Livelihoods (part of the Alternative Energy Promotion Centre's National Rural and Renewable Energy Programme), and Winrock International (a non-profit organisation working in international development) have had recent projects focused on improving the financial viability of operational MHPs (LIIFT Nepal, 2017; Winrock International, 2018). The results of this study provide evidence that the interaction of financial viability, technical reliability and community engagement should also be considered, as well as how these interactions change with time. Furthermore, the findings indicate that some plants have greater potential for unsustainable operation due to their inherent features. For all organisations working in Nepal, these outcomes should be considered during the implementation of new MHPs and programmes that support their ongoing operation.

Conclusion

Understanding the sustainability of off-grid renewable energy projects is important in comparing technologies, learning lessons for the implementation of new projects and ensuring that reliable electricity services are delivered to rural communities. The methodology used provided a basis to compare micro-hydropower sites with a combination of quantitative and qualitative data. The results were analysed considering three important areas: reliability, financial viability and community engagement. It was found that most operators conducted some regular maintenance but there was also evidence of a range of technical problems that could have manifested at earlier stages in the project cycle. Financially, communities were largely reliable in paying their tariffs but in some instances the income collected by plants was insufficient to pay for repairs. Communities were largely engaged in projects and often proud of the hard work that had been put in to develop their local plants. Overall, the sustainability of plants was heavily affected by inherent features of the plant, such as rated power and location. In addition, events both internal and external to the socio-technical system affected the sustainability of plants. An expansion of the study into more rural areas of Nepal is required to investigate differences in the sustainability of MHPs that occur due to their location.

Further work will involve developing a greater understanding of financially sustainable tariff structures and methods for their implementation with communities and the effect of access to markets upon financial viability. Technically, a survey of manufacturers will improve understanding of their approach throughout the project process. This can be used to identify design and process changes, and opportunities to introduce improvements to technology, that are focussed on improving the reliability of plants.

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